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Published in:
IASS-APCS 2012 Proceedings

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Robustness Assessment of Spatial Timber Structures

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Summary

Robustness of structural systems has obtained a renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. In order to minimise the likelihood of such disproportionate structural failures many modern building codes consider the need for robustness of structures and provide strategies and methods to obtain robustness. Therefore a structural engineer may take necessary steps to design robust structures that are insensitive to accidental circumstances. The present paper summaries issues with respect to robustness of spatial timber structures and will discuss the consequences of such robustness issues related to the future development of timber structures.

Keywords: *robustness; reliability, timber;static determinacy; redundancy; ductility; brittleness.*

1. Introduction

Timber is an efficient building material, not least in regard to its mechanical properties but also because it is a highly sustainable material considering all phases of the life cycle of timber structures: production, use and decommissioning. Timber is a widely available natural resource; with proper management, there is a potential for a continuous and sustainable supply of raw timber material in the future. Because of the low energy use and the low level of pollution associated with the manufacturing of timber structures, the environmental impact is much smaller than for structures built of other materials. Timber is a light material and compared to its weight the strength is high; the strength to weight ratio in grain direction is even higher than for steel.

However, considering its beneficial properties, timber is still not used to its full potential in the building and construction sector. Many building developers, architects and structural engineers do not consider timber as a competitive building material compared with concrete, steel or masonry. Attributes such as high performance regarding reliability, serviceability and durability are generally not associated with timber as a building material. One of the main reasons for this is that timber is a highly complex material; it actually requires a significant amount of expertise to fully appreciate the potential of timber as a structural building material. There are also a number of issues which need to be further researched before timber can achieve the same recognition as a high quality building material such as steel and concrete. It is thus not surprising that self-supporting timber structures can span over 100 meters. There are examples of such structures in Europe, America and Japan. The issue of long span has been studied for centuries in Occidental culture and, among the developed structural systems. Further by using modern CNC based fabrication tools new timber construction projects can be developed using timber structures that once required complicated handwork. This can help make visionary timber architecture possible that once would have been unimaginable. However, this renewed interest for advanced timber structures has also facilitated an intensely research concerning reliability of timber structures and robustness of timber structures [1]. In general robustness of structural systems has obtained a renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. As there is obvious correlation between the redundancy and robustness, redundant structures will, in principle, be more robust than statically determinant. The present paper will consider such robustness issues for spatial timber structures. The approach in this paper is to discuss the main principles of robustness followed by an analysis of some robustness issues like ductility which can be taken into account in design of timber structures. Thereafter solutions for structural layout are discussed which would make timber structure more robust while maintaining its properties

2. Robustness Framework

During the last years, robustness of structural systems has obtained a renewed interest due to a much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure. The interest has also been facilitated due to recently severe structural failures such as the World Trade Centre towers in 2001, Siemens Arena in 2003 and the Charles de Gaulle International Airport in 2004. In order to minimize the likelihood of such disproportionate structural failures many modern building codes [2,3] consider the need for robustness in structures and provide strategies and methods to obtain robustness.

One of the main issues related to robustness of structures is the definition of robustness. The most general definitions are very similar to each other particularly those taken from structural codes despite the use of different terms (robustness, structural integrity, but also progressive collapse prevention). These definitions are focused on the prevention from an escalation of damage within the structure, given a certain initial (localized) failure/damage. During the last decades a variety of research efforts have attempted to quantify aspects of robustness such as redundancy and identify design principles that can improve robustness [4,5]. Due to many potential means by which a local collapse in a given structure can propagate from its initial extent to its final collapse state, there is no universal approach for evaluating the potential for disproportionate collapse, or for robustness [6].

The requirement for robustness is specified in most buildings codes in a way like the general requirements in the two Eurocodes: *EN 1990 - Basis of Structural Design* [2] and *EN 1991-1-7 - Accidental Actions* [3]. *EN 1990 - Basis of Structural Design* [2] provides the basic principles, e.g. it is stated that a structure shall be 'designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause'. It also states that potential damage shall be avoided by 'avoiding, eliminating or reducing the hazards to which the structure can be subjected; selecting a structural form which has low sensitivity to the hazards considered; selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localized damage; avoiding as far as possible structural systems that can collapse without warning; tying the structural members together'. *EN 1991-1-7 - Accidental Actions* [3] provides strategies and methods to obtain robustness. Actions that should be considered in different design situations are: 1) designing against identified accidental actions, and 2) designing against unidentified actions (where designing against disproportionate collapse, or for robustness, is important). The basic concepts in robustness are presented in Figure 1 and the following issues:

a) Exposures which could be unforeseen and/or unintended effects and defects (incl. design errors, execution errors and unforeseen degradation) – e.g.
    - unforeseen action effects, incl. unexpected accidental actions
    - unintended discrepancies between the structure's actual behaviour and the design models used
    - unintended discrepancies between the implemented project and the project material
    - unforeseen geometrical imperfections
    - unforeseen degeneration
b) Local damage due to exposure (direct consequence of exposure)
c) Total (or extensive) collapse of the structure following the local damage (indirect consequence of exposure)

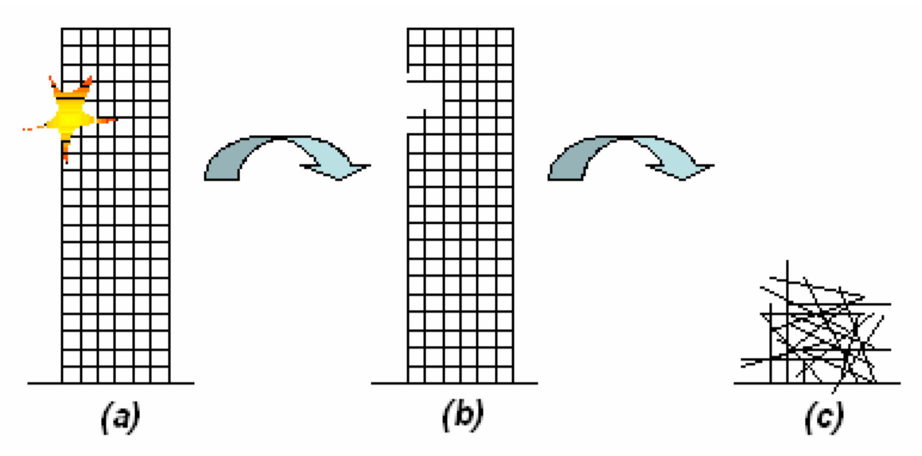

Figure 1: Illustration of the basic concepts in robustness [3].

Robustness requirements are especially related to the step from b) to c), i.e. how to avoid that a local damage develop to total collapse, i.e. robustness is meant to avoid failures caused by errors in the design and construction, lack of maintenance and unforeseeable events. During the last decades there has been a significant effort to develop methods to assess robustness and to quantify aspects of robustness. An overview of these methods is given in [4]. The basic and most general approach is to use a risk analysis where both probabilities and consequences are taken into account. Approaches to define a robustness index can be divided in the following levels with decreasing complexity [7]:

- A risk-based robustness index based on a complete risk analysis where the consequences are divided in direct and indirect risks [4]
- A probabilistic robustness index based on probabilities of failure of the structural system for an undamaged structure and a damaged structure [8,9]
- A deterministic robustness index based on structural measures, e.g. pushover load bearing capacity of an undamaged structure and a damaged structure [10].

Other simple measures of robustness have been proposed based on e.g. the determinant of the stiffness matrix of a structure with and without removal of elements. Due to many potential means by which a local collapse in a given structure can propagate from its initial extent to its final state, there is no universal approach for evaluating the potential for disproportionate collapse, or for robustness [7].

However, for reduction of the risk of collapse in the event of loss of structural element(s), a structural engineer may take necessary steps to design a collapse-resistant structure that is insensitive to accidental circumstances. This means that the following structural traits should be incorporated in the design [10]:

- *Redundancy*: incorporation of redundant load paths in the vertical load carrying system.
- *Ties*: using an integrated system of ties in three directions along the principal lines of structural framing.
- *Ductility*: structural members and member connections have to maintain their strength through large deformations (deflections and rotations) so the load redistribution(s) may take place.
- *Adequate shear strength*: as shear is considered as a brittle failure, structural elements in vulnerable locations should be designed to withstand shear load in excess of that associated with the ultimate bending moment in the event of loss of an element.
- *Capacity for resisting load reversals*: the primary structural elements (columns, girders, roof beams, and lateral load resisting system) and secondary structural elements (floor beams and slabs) should be designed to resist reversals in load direction at vulnerable locations.
- *Connections (connection strength):* connections should be designed in such way that it will allow uniform and smooth load redistribution during local collapse
- *Key elements:* exterior columns and walls should be capable of spanning two or more stories without buckling, columns should be designed to withstand blast pressure etc.
- *Alternate load path(s):* after the basic design of structure is done, a review of the strength and ductility of key structural elements is required to determine whether the structure is able to "bridge" over the initial damage.

3. Robustness Analysis and Design of Spatial Timber Structures

Recently, to reach a better understanding of aspects which influence on the robustness of timber structures several benchmarks examples have been considered in the EU COST Action E55 – 'Modelling of the performance of timber structures' [1] where the purpose and aim were:

- to investigate system reliability (spatial distribution of strength and stiffness) and robustness of timber structures using probabilistic methods.
- to model failure modes (different types incl. connections and behaviour after failure: ductile / brittle).
- to discuss how to model the effect of human errors (unintentional errors and defects).
- to model local failures – due to local extreme snow load, design/execution/maintenance errors in connections.
- to identify key elements, and how to design key elements.

In the next two sections some important results from these investigations will be outlined.

3.1 Robustness of Spatial Timber Structures taking Ductility into Account

During evolution trees have specialized in resisting their natural environment. In this respect it is a high quality fibre composite, optimally designed to resist loads acting on the tree but also to provide transport of water and nutritional agents. Stem and branches of the tree are designed to resist gravity loads and wind loads. The wood structure is adapted to create maximum strength in stressed directions, whereas in other directions the strength is quite low. As a result wood has special material properties like significant variability, anisotropy and orthotropic material properties consisting of “high strength” fibres (grains) oriented along the longitudinal axis of a timber log and packed together within a “low strength” matrix. Timber has no or a very little ductility in the tensile region, while in the compressive region linear elastic-plastic behaviour can be assumed [11]. In the aspect of timber joints all agree that the way to achieve high ductility is to take advantage of the plasticity of mechanical connectors (nails, dowels, bolts, etc.). The only certain way to create ductile structures is to design in such a way that collapse of a structure is governed by failures of mechanical (ductile) joints [12]. This is especially important for timber structures designed to resist seismic loads.

It could be assumed that the ductile behaviour of joints as well as timber material in compression could have a positive influence on the robustness of timber structures. This aspect has been analysed using an idealized model of a timber structure by a parallel system using reliability-based methods [13]. First, a parallel system consisting of *m* ideally brittle elements with strengths R_i is considered, see Figure 2. The element strengths are assumed identically distributed and statistically independent. The modulus of elasticity is assumed deterministic and with perfect equal load sharing among the elements the system strength *R* can be calculated as

$$R = \max_{i=1}^{m} \{(m-i+1) \cdot R_i\} \tag{1}$$

where the element strengths R_i are set in a decreasing order, $R_1 < R_2 < \ldots < R_m$. The load *S* is modeled by a stochastic variable. Such a system is denoted a *Daniels system* and has been analyzed in several papers with respect to system reliability for different assumptions related to stochastic variables [14,15,16].

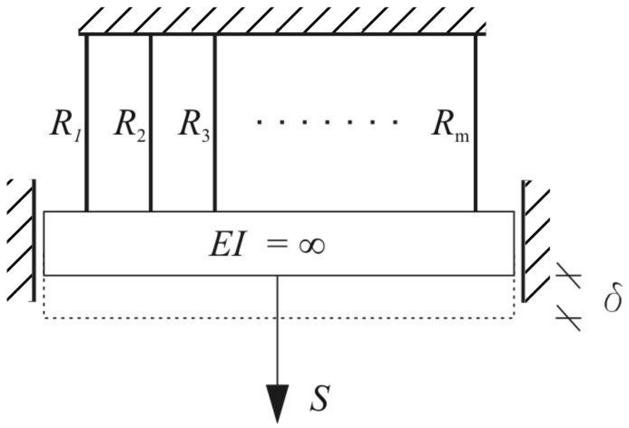

Figure 2: Mechanical model for parallel system.

For an arbitrary stochastic force-deformation curve system failure occurs if the maximum system strength is exceeded by the load for a given imposed deformation δ, i.e. the probability of failure of the parallel system is given as the intersection of the individual failure events

$$P_f^P = \left(\bigcap_{\delta} \{R_i(\delta) - S \le 0\} \right) \tag{2}$$

By using (2) [14,15,16] have presented results for probabilities of failure for the system in figure 2 under different post-failure member behaviors (ductility), correlations, strength and load variabilities and number of elements. In general it is shown that for a small number of elements the brittle system behaves much like the series system. As number of elements is increased the reliability of the parallel system is increased significantly (and vice-versa for the series system). Further, when the ductility increases linearly the reliability of the system increases much steeper (exponentially), i.e. a relatively little increase in ductility accounts for a considerable extra reliability. An increase in correlation between elements implies a system reliability decrease. In summary, if there is a moderate degree of ductility, ductile systems will provide significant extra reliability only if elements are low correlated or with no correlation at all and if the load variability is not high. On the other hand, if there is a brittle behaviour, there is a relatively little effect of the system (especially for the small systems). There is even a small negative effect for medium coefficients of strength variation.

In [11] the importance of ductility in spatial timber structures has been evaluated using the above idealized system modelling and structural reliability methods. A level of ductility was introduced as a ratio between the yielding displacement and the ultimate displacement. Different levels of ductility were assumed based on experimental results obtained with timber joints and timber beams. Based on these tentative investigations it was found that the system reliability of a structural spatial timber structure, i.e. the robustness can be increased significantly awarding the ductile behaviour.

3.2 Design for Robustness Design of Spatial Timber Structures

Design rules for robustness require insensitivity to local failure and the prevention of progressive collapse. This is often verified by applying the load case 'removal of a limited part of the structure'. In [1] typical secondary systems for timber roof structures against these requirements, including exemplary comparative calculations for typical purlin systems have been investigated. The results were compared against typical reasons for damages and failure. Applying the finding that most failures of timber structures are not caused by random occurrences or local defects, but by global (repetitive) defects (e.g. from systematic human errors mistakes), it was shown that the objective of load transfer - often mentioned as preferable - should be critically analysed for such structures.

Evaluating purlin systems from a structural perspective will highlight continuous systems due to their lowered maximum bending moments, enabling the realisation of larger spacing at given span and cross-section. Due to this and due to the acceleration of the construction process, the majority of purlin systems today are realized by continuous systems like lap-jointed beams.

The evaluation from a robustness perspective reveals more debatable results. Continuous systems (due to their redundancy and higher stiffness) will result in an increased load transfer in the case of failure of one structural member. Many publications on robustness mention this as preferable. Nevertheless, as recent studies have revealed, are most failures of structures not caused by local defects or random occurrences but by global defects from systematic mistakes or global deterioration, meaning the damaging effects are highly correlated. Such structures are not able to withstand a large load transfer and will therefore be more prone to progressive collapse. This idea is supported by [1], stating that the "alternate load path" approach (realized by e.g. parallel systems) may "in certain circumstances not prevent but rather promote collapse progression". Hence, the idea of compartmentalization is introduced which is realized by a deliberate reduction of continuity at chosen compartment borders. In this way, if progressive collapse occurs, it will affect only one compartment and at the same time reduce the probability for the total damage of the whole structure. The major goal in robustness is to prevent a sudden and unexpected failure of one element from initiating the progressive collapse, in order to save lives and to limit the size of the damages and by the related costs. The rather limited Siemens arena collapse, was obtained by reducing the connections of the purlins to the trusses to the strict minimum in order to avoid the progressive collapse [1]. Also in the case of the Bad Reichenhall ice-arena collapse, it has been proved that a strong but softer secondary system will have prevented the structure from the overall collapse.

In summary this means, that there is no strategy for the structural designer, which ensures robustness in all cases. When deciding on a robustness strategy one has to consider different scenarios. The major difference is weather the cause of failure is likely to be a systematic (mostly human) error or an unforeseeable (mostly local) incident. Experience tells that human errors are by far the most common cause. In order to reduce the risk of collapse and in particular progressive collapse, it is crucial to reduce the number of human errors by e.g. enhanced quality control. Only then it would be possible to choose an unambiguously beneficial robustness strategy. One approach could be to introduce diversity and indeterminacy into the structure, e.g. by designing a structure with many different elements, i.e. avoiding too much symmetry and repetition and possibilities for redistribution of loads. It is the belief that the given statements are valid for the majority of timber structures [1].

4. Conclusions

The present paper summaries issues with respect to robustness of spatial timber structures and will discuss the consequences of such robustness issues related to the future development of timber structures. First, a framework for robustness of structures is discussed. Next, robustness assessment of timber structures has been considered where the relationship between system reliability and the characteristics ductility and redundancy are established. Tentative results indicate that the system reliability of a structural spatial timber system can be increased significantly awarding the ductile. Further, design for robustness of spatial timber structures has been discussed. However, to put some of the discussed issues on a broader foundation, further comparative calculations on different spatial timber systems should be carried out.

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